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S -integral points on elliptic curves - Notes on a paper of B. M. M. de Weger

par EMANUEL HERRMANN* et ATTILA PETHŐ**

RÉSUMÉ. Nous donnons une nouvelle preuve beaucoup plus courte d'un résultat de B. M. M de Weger. Cette preuve est basée sur la théorie des formes linéaires de logarithmes complexes, p -adiques et elliptiques, pour lesquelles nous obtenons une majoration en confrontant les résultats de Hajdu et Herendi à ceux de Rémond et Urfels.

ABSTRACT. In this paper we give a much shorter proof for a result of B.M.M de Weger. For this purpose we use the theory of linear forms in complex and p -adic elliptic logarithms. To obtain an upper bound for these linear forms we compare the results of Hajdu and Herendi and Rémond and Urfels.

1. Introduction

In a recent paper [12] B.M.M. de Weger solved the Diophantine equation
(1)
$$y^2 = x^3 - 228x + 848$$

completely in rational numbers x, y such that their denominator in the lowest form is a power of 2. With other words, he solved (1) in S -integers where $S = \{2, \infty\}$. De Weger uses in the proof algebraic number theoretical considerations and lower estimates for linear forms in complex and q -adic logarithms of algebraic numbers.

In the present paper we will give a much shorter proof of a generalization of Theorem 1 of [12]. Here we use the theory of elliptic curves and linear forms in elliptic logarithms. More precisely, we are using a theorem of Rémond and Urfels [6], which can be applied for curves of rank at most 2. An alternative method which avoids lower bounds for linear forms in q -adic elliptic logarithms is given in [5]. However the bounds coming from [5] are

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in the actual case much larger as working directly with the Theorem of Rémond and Urfels (cf. Section 3).

We now state our result.

Theorem 1. *Let $S = \{2, 3, 5, 7, \infty\}$. Then the equation*

$$y^2 = x^3 - 228x + 848$$

has only 65 S -integer solutions $(x, \pm y)$ listed in Table 2 at the end of this paper.

2. Notations and Auxiliary Results

Let the elliptic curve be defined by the equation

$$(2) \quad y^2 = x^3 + Ax + B, \quad A, B \in \mathbb{Z}.$$

Let $S = \{q_1, \dots, q_{s-1}, q_s = \infty\}$ be a set of primes including the infinite prime. To simplify the presentation we assume that the equation (2) is minimal for every finite prime $q \in S$. For the general case we refer to the paper [5].

Let P_1, \dots, P_r denote a basis of the Mordell-Weil group $E(\mathbb{Q})$ and let g be the order of the torsion subgroup $E_{\text{tors}}(\mathbb{Q})$ of $E(\mathbb{Q})$. Let \hat{h} denote the Néron-Tate height on $E(\mathbb{Q})$. Designate by λ the smallest eigenvalue of the positive definite regulator matrix $(\hat{h}(P_i, P_j))_{1 \leq i, j \leq r}$.

Let $\wp(u)$ be the Weierstrass \wp -function corresponding to the curve $E(\mathbb{C})$. Let $\Omega = \langle \omega_1, \omega_2 \rangle$ be its fundamental lattice and ω_1 its real period. There exists, for any $P = (x, y) \in E(\mathbb{C})$, an element $u \in \mathbb{C}/\Omega$ such that $(x, y) = (\wp(u), \frac{1}{2}\wp'(u))$. This is called the (*complex*) *elliptic logarithm* of P . In the sequel $u_{i, \infty}$ denotes the elliptic logarithm of P_i for $i = 1, \dots, r$. We put $u'_{i, \infty} = g \frac{u_{i, \infty}}{\omega_1}$.

For a finite prime $q \in S$ let $E_0(\mathbb{Q}_q)$ denote the points of $E(\mathbb{Q}_q)$ with non-singular reduction modulo q . Then the index $[E(\mathbb{Q}_q) : E_0(\mathbb{Q}_q)]$ is finite, and equal to the Tamagawa number c_q because by our assumption equation (2) is minimal at q . Let further \tilde{E} denote the reduced curve E modulo q . Let $\mathcal{N}_q = \#\tilde{E}(\mathbb{F}_q)$ be the number of rational points of \tilde{E}/\mathbb{F}_q . With the order g of the torsion group, we define the number

$$m = m_q = \text{lcm}(g, c_q \cdot \mathcal{N}_q).$$

Finally for the finite places $q \in S$, let $u'_{i, q}$ denote the q -adic elliptic logarithm of mP_i for $i = 1, \dots, r$. For the definition and basic properties of q -adic elliptic logarithms we refer to Silverman [7] and to [5]. Now we state the main result of [5] in the special case considered, i.e. for curves given in short Weierstrass form.

Theorem A. *Let the elliptic curve $E(\mathbb{Q})$ be defined by equation (2), which is minimal for every finite prime $q \in S$. Assume that the S -integral point*

$P = (x, y) \in E(\mathbb{Z}_S)$ has the representation

$$(3) \quad P = \sum_{i=1}^r n_i P_i + T$$

with $n_i \in \mathbb{Z}, i = 1, \dots, r$, and T a torsion point of $E(\mathbb{Q})$. For $N(P) = \max\{|n_i|, i = 1, \dots, r\}$, we have

$$(4) \quad N(P) \leq N_0 = \sqrt{\frac{1}{\lambda}(\frac{k_1}{2} + k_2)}$$

with $k_2 = \log \max\{|2A|^{1/2}, |4B|^{1/3}\}$,

$$k'_1 = 7 \cdot 10^{38s+49} s^{20s+15} Q^{24} (\log^* Q)^{4s-2} k_3 (\log k_3)^2 ((20s - 19)k_3 + \log(ek_4)),$$

$$k_1 = k'_1 + 2 \log 6,$$

where $\log^* Q = \max\{\log Q, 1\}$ for $Q = \max\{q_1, \dots, q_{s-1}\}$, $s = \#S$,

$$k_3 = \frac{32}{3} \sqrt{|\Delta_0|} \left(8 + \frac{1}{2} \log |\Delta_0|\right)^4,$$

$$k_4 = 10^4 \max\{16A^2, 256\sqrt{|\Delta_0|^3}\}$$

with $\Delta_0 = 4A^3 + 27B^2$. Moreover, there exists a place $q \in S$ such that

$$(5) \quad \left| \sum_{i=1}^r n_i u'_{i,q} + n_{r+1} \right|_q \leq k_5 \exp\left\{-\frac{\lambda}{s} N(P)^2 + \frac{k_2}{s}\right\}$$

with $n_{r+1} \in \mathbb{Z}$ if $q = \infty$ and $n_{r+1} = 0$ otherwise, and with $k_5 = \frac{2g}{3\omega_1}$ if $q = \infty$ and $k_5 = 1$ otherwise.

Theorem A together with numerical Diophantine approximation techniques is sufficient to prove our Theorem 1. However it was pointed out already in [5] that combining the method of Smart [8] with results of David [2] and of Rémond and Urfels [6] one can obtain a much better estimate for $N(P)$ as by the one implied by Theorem A. In the sequel we assume $r \leq 2$. To formulate the next theorem we have to introduce further notations. Let

$j = \frac{j_1}{j_2}$ with $j_1, j_2 \in \mathbb{Z}$ and $\gcd(j_1, j_2) = 1$ be the j -invariant of $E(\mathbb{Q})$. Put

$$\begin{aligned} h &= \log \max\{4|Aj_2|, 4|Bj_2|, |j_1|\}, \\ \log V_i &= \max\left\{\hat{h}(P_i), h, \frac{3\pi|u'_{i,\infty}|_\infty^2}{\text{Im}\tau}\right\}, \quad i = 1, 2, \\ \log V_0 &= \max\left\{h, \frac{3\pi}{\text{Im}\tau}\right\}, \\ k_{6,\infty} &= \frac{k_2 + s \log k_5}{\lambda}, \\ k_{7,\infty} &= \frac{2 \cdot 10^{68} \cdot s \cdot h^5}{\lambda} \prod_{i=0}^2 \log V_i. \end{aligned}$$

For a finite place $q \in S$ let

$$\begin{aligned} \alpha_q &= \begin{cases} 3, & \text{if } q = 2 \\ \frac{1}{q-1}, & \text{otherwise} \end{cases} \\ \sigma_q &= (q^{\alpha_q} \max\{|u'_{1,q}|_q, |u'_{2,q}|_q\})^{-1}, \\ d_q &= \max\{1, 1/\log \sigma_q\}, \\ a_i &= \max\{1, \hat{h}(P_i)\}, \quad i = 1, 2, \\ \beta &= \max\{\log N(P), \log |A|_\infty, \log |B|_\infty, a_1, a_2, d_q\}, \\ \gamma &= \max\{\log |A|_\infty, \log |B|_\infty, \log \beta\}, \\ k_{6,q} &= \frac{k_2}{\lambda}, \\ k_{7,q} &\geq (3.6 \cdot 10^{25} s \cdot a_1 a_2 d_q^6 \log \sigma_q) / \lambda. \end{aligned}$$

Theorem B. *Assuming that $r \leq 2$ and using the notations introduced in Theorem A and above we have*

$$N(P) \leq N_1 := \max\{N_q : q \in S\},$$

where

$$N_q = \begin{cases} 2^5 \sqrt{k_{6,\infty} k_{7,\infty}} (\log 5^5 k_{7,\infty})^{5/2}, & \text{if } q = \infty, \\ 2^4 \sqrt{k_{6,q} k_{7,q}} (\log 4^4 k_{7,q})^2, & \text{if } q \in S \setminus \{\infty\}. \end{cases}$$

Proof. Combining inequality (5) with the lower bounds for linear forms in elliptic logarithms due to David [2] and for linear forms in at most two q -adic elliptic logarithms due to Rémond and Urfels [6] one obtains the upper bound for $N(P)$ analogously as described for example in Gebel, Pethő and Zimmer [3, 4]. Therefore we omit the details. □

3. Proof of Theorem 1

3.1. Basic data of the elliptic curve. In the sequel we denote by E the elliptic curve over \mathbb{Q} defined by equation (1). Let $S = \{2, 3, 5, 7, \infty\}$. It is easy to check, that (1) is minimal for every finite prime $q \in S$. Actually, it is a global minimal model of E . The discriminant of E is $\Delta = -16\Delta_0$ with $\Delta_0 = -27993600$. We have

$$E(\mathbb{Q}) \simeq \mathbb{Z}/2\mathbb{Z} \oplus \mathbb{Z}^2,$$

where the only non-trivial torsion point is $(4, 0)$ and a basis of the infinite part of the Mordell-Weil group is $P_1 = (-2, 36), P_2 = (-11, 45)$. (See Tzanakis [10], or one of the programs *apecs* [13], *Magma*¹ [1], *mwrnk* [14] or *Simath* [15].)

Now we can compute the fundamental parallelogram of the associated Weierstrass \wp -function and get

$$\omega_1 = 0.767848, \quad \omega_2 = -0.631356 \cdot i \quad \text{and} \quad \tau = \frac{\omega_1}{\omega_2} = 1.216188 \cdot i.$$

The regulator matrix of E is

$$R = \begin{pmatrix} 0.423441 & -0.158771 \\ -0.158771 & 0.906408 \end{pmatrix},$$

hence its smallest eigenvalue is given by $\lambda = 0.375922$.

Using Tate's algorithm [9] we compute the Tamagawa numbers

$$c_2 = 4, \quad c_3 = 4, \quad c_5 = 2 \quad \text{and} \quad c_7 = 1.$$

The curve E has additive reduction at the primes 2 and 3, multiplicative reduction at 5 and good reduction at 7. Hence,

$$\mathcal{N}_2 = 2, \quad \mathcal{N}_3 = 3, \quad \mathcal{N}_5 = 6 \quad \text{and} \quad \mathcal{N}_7 = 12.$$

Using these data we can compute the numbers m_q and obtain

$$m_2 = 8, \quad m_3 = 12, \quad m_5 = 12 \quad \text{and} \quad m_7 = 12.$$

3.2. Upper Bounds for $N(P)$.

(i) The first way to obtain an upper bound for $N(P)$ is to calculate N_0 of Theorem A. We have actually $Q = 7, s = 5$,

$$k_2 = \log \max\{456^{1/2}, 3392^{1/3}\} = 3.061246,$$

$$k_3 = \frac{32}{3} \sqrt{|\Delta_0|} \left(8 + \frac{1}{2} \log |\Delta_0|\right)^4 = 4.258342 \cdot 10^9,$$

$$(6) \quad k_4 = 10^4 \max\{16 \cdot 228^2, 256 \cdot |\Delta_0|^{3/2}\} = 3.791649 \cdot 10^{17}$$

and $k_1 = 3.730724 \cdot 10^{369}$, hence $N(P) \leq N_0 = 7.044216 \cdot 10^{184}$.

(ii) Another, a bit more complicated, way to find an upper bound for $N(P)$ is to compute $N_1 = \max\{N_q : q \in S\}$ as defined in Theorem B.

¹Magma version 2.6 will have an implementation of the algorithm described in [5].

Consider first the case $q = \infty$. Then we have

$$\begin{aligned}
 h &= \log \max\{4 \cdot 228 \cdot 75, 4 \cdot 848 \cdot 75, 2^5 \cdot 19^3\} = 12.446663, \\
 \log V_0 &= \max\{h, \frac{3\pi}{\text{Im}\tau}\} = 12.446663, \\
 \log V_1 &= \max\{\hat{h}(P_1), h, \frac{3\pi q^2 |u_{1,\infty}|^2}{\omega_1^2 \text{Im}\tau}\} = 21.645104, \\
 \log V_2 &= \max\{\hat{h}(P_2), h, \frac{3\pi q^2 |u_{2,\infty}|^2}{\omega_1^2 \text{Im}\tau}\} = 28.279603, \\
 k_{5,\infty} &= \frac{4}{3\omega_1} = 1.736455, \\
 k_{6,\infty} &= 15.483196, \\
 k_{7,\infty} &= 6.054145 \cdot 10^{78}.
 \end{aligned}$$

Thus we obtain $N_\infty \leq 1.530526 \cdot 10^{47}$ after a simple computation.

Next we have to consider the cases $q = 2, 3, 5$ and 7 . In Table 1 below you find the actual values of α_q, σ_q and d_q .

Table 1

q	2	3	5	7
α_q	3	1/2	1/4	1/6
σ_q	2	$3^{1/2}$	$5^{3/4}$	$7^{5/6}$
d_q	$1/\log 2$	$2/\log 3$	1	1
$k_{7,q}$	$2.992592 \cdot 10^{27}$	$9.5742 \cdot 10^{27}$	$5.779766 \cdot 10^{26}$	$7.76455 \cdot 10^{26}$

The following values are independent of $q \in \{2, 3, 5, 7\}$

$$\begin{aligned}
 a_1 &= \max\{1, \hat{h}((-2, 36))\} = \max\{1, 0.423441\} = 1, \\
 a_2 &= \max\{1, \hat{h}((-11, 45))\} = \max\{1, 0.906408\} = 1, \\
 k_{6,q} &= k_2/\lambda = 8.143301.
 \end{aligned}$$

Choosing the worst cases from Table 1 we see that we can take

$$k_{7,q} = k_{7,3} = 9.5742 \cdot 10^{27}, \quad q = 2, 3, 5, 7,$$

thus

$$N_q = N_3 = 2.187487 \cdot 10^{19}, \quad q = 2, 3, 5, 7.$$

These inequalities imply

$$N(P) \leq N_1 = \max\{N_q : q \in S\} = 1.530526 \cdot 10^{47}$$

by Theorem B. Since N_1 is much smaller than N_0 we use this value in the sequel.

3.3. Reduction of the large upper bound for $N(P)$. By Theorem 1, and by the last section we have to solve the Diophantine approximation problem

$$|n_1u'_{1,q} + n_2u'_{1,q} + n_3|_q \leq k_5 \exp\{0.075184 \cdot N(P)^2 + 0.6122492\},$$

$$N(P) \leq N_1 = 1.530526 \cdot 10^{47}$$

for each $q \in S$.

To solve these systems we use the well known reduction procedure of de Weger [11]. (See also Smart [8].) For details about the high precision computation of q -adic elliptic logarithms we refer to Pethő et al. [5]. We shall also use the notations introduced there.

We first take $q = \infty$ and perform a de Weger reduction with $C = 10^{142}$. We obtain the new upper bound $N(P) \leq M_\infty = 67$ in the case $q = \infty$. Comparing this bound with $N_q, q = 2, 3, 5, 7$ we obtain

$$N(P) \leq N_3 = 2.187487 \cdot 10^{19},$$

i.e. we may perform the q -adic reduction steps with this value.

To do this we compute for each $q \in S \setminus \{\infty\}$, the q -adic elliptic logarithms of $m_q P_i, i = 1, 2$, with precision at least

$$n_2 = 129, \quad n_3 = 82, \quad n_5 = 56, \quad n_7 = 46.$$

This precision is necessary to carry out the q -adic de Weger reduction. For this purpose we use the method of [5].

$$u'_{1,2} = 134584334573222732131510464853384888320 + O(2^{128})$$

$$u'_{2,2} = 224603122385055121905025779589746548856 + O(2^{128})$$

$$u'_{1,3} = 35130898366670225251067310603381664587 + O(3^{81})$$

$$u'_{2,3} = 32674326287561878726624624078558984866 + O(3^{81})$$

$$u'_{1,5} = 118414103305724592543524002578287458095 + O(5^{55})$$

$$u'_{2,5} = 193714651202697832194263283063279750580 + O(5^{55})$$

$$u'_{1,7} = 49086609441793589144883973076015987885 + O(7^{46})$$

$$u'_{2,7} = 723939447229120403790851561285560713079 + O(7^{46})$$

Now we perform the q -adic de Weger reduction with the values $C_2 = 2^{128}, C_3 = 3^{81}, C_5 = 5^{55}$ and $C_7 = 7^{46}$ and obtain the new bound

$$N(P) \leq \max\{\mathcal{M}_\infty = 67, \mathcal{M}_2 = 12, \mathcal{M}_3 = 13, \mathcal{M}_5 = 13, \mathcal{M}_7 = 13\}.$$

This new upper bound for $N(P)$ can be further reduced. On repeating this reduction process 3-times, we eventually get $N(P) \leq 13$, which cannot be reduced any further.

Table 2

S -integral points $P = (x, y) = \left(\frac{\xi}{\zeta^2}, \frac{\eta}{\zeta^3} \right) = \sum_{i=1}^2 n_i P_i + T_j$, $j = 0, 1$
 on $E : y^2 = x^3 - 228x + 848$ for $S = \{2, 3, 5, 7, \infty\}$

rank	2				
basis	$P_1 = (-2, 36), P_2 = (-11, 45)$				
torsion	$T_0 = \mathcal{O}, T_1 = (4, 0)$				
#	ξ	η	ζ	F	(n_1, n_2, j)
1	4	0	1		(0, 0, 1)
2	-11	45	1		(0, 1, 0)
3	16	36	1		(0, 1, 1)
4	94	-900	1		(1, -1, 0)
5	2	-20	1		(1, -1, 1)
6	-2	36	1		(1, 0, 0)
7	34	180	1		(1, 0, 1)
8	14	-20	1		(1, 1, 0)
9	-14	-36	1		(1, 1, 1)
10	754	-20700	1		(1, 2, 1)
11	196	2736	1		(2, -1, 1)
12	13	9	1		(2, 0, 0)
13	-16	20	1		(2, 0, 1)
14	52	-360	1		(2, 1, 1)
15	53	371	1		(2, 2, 0)
16	814	23220	1		(3, 1, 0)
17	534256	-390502764	1		(4, 3, 1)
18	97	-783	2	2	(0, -2, 0)
19	1	-225	2	2	(2, 1, 0)
20	857	-25027	2	2	(4, 0, 0)
21	49	855	4	2^2	(2, -1, 0)
22	-16439	-631035	32	2^5	(2, 3, 0)
23	-44	-1160	3	3	(0, -2, 1)
24	34	172	3	3	(3, 1, 1)
25	1534	42020	9	3^2	(3, -1, 0)
26	94	-828	5	5	(1, 2, 0)
27	629	-13133	5	5	(2, -2, 0)
28	-194	-5796	5	5	(3, 0, 0)
29	6361	-282141	20	$2^2 \times 5$	(4, 2, 0)
30	-818	-468	7	7	(1, -2, 0)
31	16	9540	7	7	(2, 2, 1)
32	946	-20700	7	7	(3, 0, 1)
33	8516	1163623840	343	7^3	(4, -2, 1)

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